Effects of mild alternate wetting and drying irrigation and rice straw application on N_2O emissions in rice cultivation

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Abstract. The shortage of water resources and the decline in soil organic matter (SOM) are critical limiting factors affecting the improvement in rice productivity, while alternate wetting and drying (AWD) irrigation and recycling application of rice straw are considered favourable mitigation measures. However, the impact of such measures on rice yield and greenhouse gas (GHG) emissions, especially nitrous oxide (N_2O) emissions, needs to be further clarified to ensure that agronomic practises save water, conserve soil, and reduce GHG. Therefore, we explored the effects of mild AWD irrigation combined with on-site rice straw recycling on N_2O emissions and rice yield through rice pot experiments. This experiment included two irrigation methods (continuous flooding (CF) irrigation and mild AWD irrigation), two nitrogen (N) application levels (0 and 225 kg N ha^{-1}) and two rice straw (S) return levels (0 and 9000 kg ha^{-1}), for a total of 10 treatments, and each treatment had three replicates. ^{15}N-urea and ^{15}N-S were added to the soil. The results showed that N_2O emissions were primarily affected by urea application and irrigation methods, with urea application being most important. Compared with CF irrigation, mild AWD irrigation increased cumulative N_2O emissions, with an average increase of 28.8%. In addition, adding rice straw to mild AWD irrigation further stimulated N_2O emissions by 18.1%. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation increased the yield-scaled N_2O emissions by 17.9%, and the addition of rice straw further promoted the yield-scaled N_2O emissions under mild AWD irrigation by 17.4% but reduced the global warming potential (GWP) (methane (CH_4) + N_2O) by 62.9%. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation

reduced the uptake of soil-derived N and aboveground biomass of rice but did not reduce rice yield. Therefore, mild AWD irrigation combined with rice straw return may be a promising agronomic method to maintain rice yield, reduce greenhouse gases, and protect or improve soil fertility.

1 Introduction

Rice is a staple food for more than half of the world's population and ensuring rice production is crucial to food security (Tang and Cheng, 2018). More than 135 million hectares of rice are cultivated worldwide, and approximately 90% of paddy fields are submerged (Wang et al., 2017a). Feeding a growing population under water scarcity will be a major challenge to Asia's food security in the coming decades (Lampayan et al., 2015). In China, more than 60% of freshwater resources are consumed by rice cultivation every year, which represents a great waste of freshwater and causes many environmental problems, such as nonpoint source pollution, eutrophication, and GHG emissions (Liao et al., 2020). Therefore, it is urgent to explore new methods for managing paddy field fertilization that can ensure high rice yield and reduced water waste and pollution.

AWD irrigation is an effective water-conserving irrigation method that can save approximately 23% of freshwater resources compared with CF irrigation (Bouman and Tuong, 2001; Chu et al., 2014). There are usually two approaches to alternate wetting and drying irrigation: severe AWD irrigation (soil water potential ≥ -30±5 kPa) and mild AWD irrigation (soil water potential ≥ -15±5 kPa) (Zhou et al., 2017). Severe AWD irrigation could reduce rice yield by 22.6% due to water stress, but under mild AWD irrigation, rice yield can be stable or slightly increased (Carrijo et al., 2017; Zhou et al., 2017). Therefore, mild AWD irrigation may offer a more promising paddy field management model. Previous studies have shown that AWD irrigation can significantly reduce CH_4 emissions but considerably promotes N_2O emissions, while GWP mitigation is dependent on the magnitude of the increase in the release of N_2O (Lagomarsino et al., 2016; Liang et al., 2017; Kritee et al., 2018; Tan et al., 2018). Therefore, exploring the impact of mild AWD irrigation on GHG emissions, especially N_2O, is conducive to reducing paddy field emissions and maximizing agricultural and environmental benefits.

Long-term cultivation without organic matter supplementation leads to serious degradation of cultivated land and reduction in soil organic matter (SOM) content (Zhou et al., 2021), which is not conducive to rice production and sustainable agricultural development (Chen et al., 2016). Straw return to the field is a valuable measure for improving SOM (Huang et al., 2021), and it is beneficial for reducing the environmental pollution caused by burning straw or discarding it randomly (Wang et al., 2018). In addition, rice straw return may cause changes in paddy field

GHG emissions (Naser et al., 2007; Ye et al., 2017; Sun et al., 2018; Yu et al., 2021), N use efficiency (Liu et al., 2021), and rice yield (Chen et al., 2016; Ku et al., 2019). Although there have been many studies on mild paddy AWD irrigation or rice straw return, few studies have focused on the effects of mild AWD irrigation combined with rice straw return on rice cultivation. Under the conventional fertilization mode, whether mild AWD irrigation combined with rice straw return can achieve the optimal goals of water saving, yield increase, and reduction in greenhouse gas emissions has remained unclear. Therefore, the purpose of this study was to investigate the effect of mild AWD irrigation combined with rice straw return on N_2O emissions and rice yield in rice cultivation and to explore the supply of N to rice growth from the soil, urea, and rice straw using ^{15}N labelling technology. Our initial hypotheses were that: 1) Mild AWD irrigation would promote N_2O emissions in rice cultivation; and 2) Mild AWD irrigation would maintain or promote rice yield.

2 Materials and methods

2.1 Experimental setup

A pot experiment was conducted in an open greenhouse at the Shenyang Experimental Station of the Institute of Applied Ecology, Liaoning Province, China (43°32'N, 123°23'E) from June 17th to October 27th, 2020. The test soil was an Alfisol with a total C content of 16.01 g/kg and a total N content of 1.36 g/kg.

The pot experiment used a random block design, including 30 pots (30 cm diameter × 20 cm height). This experiment included two irrigation methods, two N application levels, and two rice straw return levels, with three replicates of each combination, for a total of 30 rice pots (urea and straw were labelled with ^{15}N, respectively). The two irrigation methods were CF irrigation and mild AWD irrigation. CF irrigation maintained a water level depth of approximately 3-5 cm throughout the rice-growing season. Mild AWD irrigation water management in the first 7 days was consistent with CF irrigation and allowed to evaporate under monitoring; when the soil negative pressure gauge reached -15 kPa, it was sub-flooded to a depth of 3-5 cm again and then naturally allowed to dry again. This step was repeated until harvest. CF and mild AWD irrigation were halted 2 weeks before harvest. N was applied at 0 kg N ha^{-1} (CK (control check) and ^{15}S (rice straw)) and 225 kg N ha^{-1} (106.13 mg kg^{-1} dry soil) (^{15}U (urea), $U^{15}S$ (urea + rice straw) and ^{15}US (urea + rice straw)). The abundance of urea ^{15}N was 10.20%. Urea was applied three times: base fertilizer 40% (June 17^{th}), tiller topdressing 30% (August 4^{th}) and heading topdressing 30% (August 25^{th}). Rice straw return was applied at 0 kg ha^{-1} (CK and ^{15}U) and 9,000 kg ha^{-1} (4.25 g kg^{-1} dry soil) (^{15}S, $U^{15}S$ and ^{15}US). The total N content of unlabelled rice straw was 0.72%, and the isotope abundance of ^{15}N was 0.59%. The total N content of labelled rice straw was 0.73%, and the ^{15}N isotope abundance was

22.94%. The rice straw was ground and applied together with the base fertilizer. Phosphate fertilizer was superphosphate (150 kg P_2O_5 ha^{-1}), and potassium fertilizer was potassium chloride (185 kg K_2O ha^{-1}) as a one-time application of basic fertilizer. Every pot was filled with 10.51 kg (9 kg dry soil) of sieved (2 mm) fresh soil. Two hills of rice were planted in each pot. At maturity, the rice yield and aboveground biomass were recorded after being oven dried (105 ℃ for 0.5 h and 60 ℃ for 12 h).

2.2 Soil sample collection and analysis

At the regreening stage, tillering stage, jointing stage, booting stage, filling stage, and maturity stage, five points were randomly selected from the 0-10 cm soil layer of each pot and mixed. The soil NH_4^+-N and NO_3^--N were extracted with 2 mol L^{-1} KCl solution (Wu et al., 2019), filtered and analysed with a continuous flow analyser (AA3, Bran + Luebbe, Germany). The extraction of soil ^{15}N-NH_4^+-N followed Yu et al. (2020). Soil microbial biomass N (MBN) was fumigated with chloroform, extracted with 0.5 mol L^{-1} K_2SO_4 (soil: solution = 5 g: 20 ml) (Joergensen et al., 1996), and determined by a TOC analyser (Elementar vario TOC Analyzer, Germany). The soil ^{15}N-NH_4^+-N content, ^{15}N-MBN and ^{15}N of rice aboveground biomass were determined by a stable isotope ratio mass spectrometer (253 MAT, Thermo Finnigan, Germany).

2.3 Gas sampling and calculation

The static chamber method was used to determine the N_2O flux (Li et al., 2018a). The static chamber with a top seal made of transparent plexiglass consisted of two parts, namely, the base and the gas collecting chamber. The base had a diameter of 31 cm, a groove in the middle, and a height of 10 cm. The gas-collecting chamber had a diameter of 30 cm and a height of 70 cm. A small fan and a thermometer were installed in the gas-collecting chamber. N_2O was collected every two days in the first week after fertilization or irrigation and every seven days during other periods. N_2O was sampled at 8:00–11:00 a.m. each sampling day. Every pot was sealed with water when N_2O was collected. Three gas samples were collected at 0, 30 and 60 min after the chamber was airtight, and N_2O was collected with a 50 mL injector and then injected into 200 mL gasbags.

The N_2O concentration was analysed using a gas chromatograph (Agilent 7890B, Gas Chromatograph, Delaware, USA). The calculation of N_2O fluxes was as follows (Li et al., 2018a):

$$F = \rho \times h \times dc/dt \times 273/(273 + T)$$

where F is the N_2O flux (μg m^{-2} h^{-1}); ρ is the N_2O standard-state density (1.964 kg m^{-3}); h is the chamber height above the soil (m); c is the N_2O concentration; dc/dt is the slope of the N_2O concentration curve, estimated using a linear regression model (Vitale et al., 2017); 273 is the gas constant; and T is the average air temperature inside the chamber during N_2O collection (℃).

Cumulative N_2O emissions (CE) were calculated using the following formula according to Wang et al. (2011):

$$CE\ (kg\ N_2O\ ha^{-1}\ ) = \sum_{i=1}^{n}(\frac{F_i + F_{i+1}}{2})(t_{i+1} - t_i) \times 24 \times 10^{-2}$$

where *i* is the various sampling times, *t* is the sampling date, *n* is the total measurement time and 10^{-2} is the conversion factor.

The contribution of ^{15}N markers to NH_4^+-N and MBN and the calculation of the N source of the aboveground biomass of rice followed Ma et al. (2015). Yield-scaled N_2O was calculated as the ratio between N_2O and rice yield (Li et al., 2018a).

2.4 Statistical analysis

All analyses were performed using SPSS Statistics 16.0 (SPSS, Inc., Chicago, USA). One-way ANOVA was conducted to test the treatment effects with Duncan's test. Significant differences were set at alpha = 0.05. Univariate analysis of variance was used to analyse the response of cumulative N_2O emissions to irrigation method, N level and rice straw application (Table 2). Tables and figures were prepared with Excel 2016 (Microsoft Corp., USA) and Origin 8 (Origin Lab Corp., USA), respectively. The data in the figures and tables are the average value ± standard error.

3 Results

3.1 N_2O flux

Three higher N_2O flux peaks appeared after basal fertilizer and two topdressing treatments (Figure 1), and the N_2O flux peak after basal fertilizer application was significantly larger than the last two peaks. After basal fertilizer was applied, the N_2O flux peaks of CF irrigation and mild AWD irrigation were similar. After the first topdressing, the N_2O flux peak of mild AWD irrigation was significantly greater than that of CF irrigation, approximately 1.4 and 9.1 times under the U and US treatments, respectively. In contrast, the N_2O flux peak of CF irrigation after the second topdressing was 3.5 and 1.6 times higher than that of mild AWD irrigation under the U and US treatments, respectively. In addition to the above three peaks, the N_2O flux of CF irrigation was close to zero, and mild AWD irrigation had a lower flux peak with alternating wet and dry conditions. The flux of N_2O ranged from -103.93 to 2,770.50 μg m^{-2} h^{-1}. The N_2O flux appeared negative in the late stage of rice growth. The N_2O fluxes of CF irrigation and mild AWD irrigation were similar in the later stage of rice growth, indicating that drainage had little effect on it. During the entire rice growth cycle, the N_2O flux of the CK and S treatments was low. There were significant differences in the peak N_2O fluxes between the different treatments. Compared with CK, the application of rice straw alone significantly promoted the N_2O flux on the first day after CF irrigation and mild AWD irrigation. Compared with U, the addition of rice straw in CF irrigation reduced the N_2O flux, while the addition of rice straw in mild AWD irrigation increased the N_2O flux.

3.2 Soil NH_4^+-N, NO_3^--N and MBN concentrations

The soil NH_4^+-N, NO_3^--N, and MBN concentrations varied with the growing stage of rice (Fig. 2A, 2C and Fig. 3A). The soil NH_4^+-N concentration first increased and then decreased. The NH_4^+-N concentration under CF irrigation and mild AWD irrigation was low in the late rice growth period (Fig. 2A). The concentration of NO_3^--N in CF-irrigated soil showed a trend of first increasing and then decreasing and was at a low level in the later growth period of rice, while the concentration of NO_3^--N in mild AWD irrigation showed a trend of first decreasing and then increasing, with repeated decreases and increases (Fig. 2C). The concentration of MBN in CF-irrigated soil first decreased and then increased and then decreased to a lower level, while the concentration of MBN in mild AWD-irrigated soil decreased with the growth stage of rice (Fig. 3A).

There were significant differences in the NH_4^+-N, NO_3^--N, and MBN concentrations between the different treatments. In CF irrigation and mild AWD irrigation, the U treatment had a higher NH_4^+-N concentration in the early stage of rice growth, while the other treatments had no significant difference, but as rice grew, the NH_4^+-N concentration of the US treatment increased, which was significantly greater than that of the U, S and CK treatments (Fig. 2A). In CF irrigation, the NO_3^--N concentration of the U treatment was slightly higher than that of the other treatments, and all treatments had little variance. In mild AWD irrigation, the NO_3^--N concentration of the US treatment was significantly higher than that of the U, S and CK treatments. The U treatment had a higher NO_3^--N concentration than the S and CK treatments in the later stage of rice growth (Fig. 2C). The US treatment in CF irrigation and mild AWD irrigation had the highest MBN concentration during the rice growth period (Fig. 3A).

Figure 2B shows that the NH_4^+-N in CF irrigation and mild AWD irrigation mainly came from urea rather than rice straw, and the combined application of urea and rice straw further promoted the release of NH_4^+-N from urea. Regardless of CF irrigation or mild AWD irrigation, rice straw N was difficult to utilize by microorganisms in the first year under single rice straw application, but rice straw and urea combined application significantly promoted the utilization of rice straw N by microorganisms. Urea combined with rice straw application may be more easily utilized by microorganisms than urea applied alone (Fig. 3B).

3.3 Sources of aboveground biomass N in rice

As shown in Fig. 4, under CF irrigation and mild AWD irrigation, compared with CK, a single application of rice straw did not increase the aboveground N absorption of rice, while the U and US treatments significantly promoted the aboveground N absorption of rice. Under mild

AWD irrigation, the US treatment reduced N uptake in rice shoots compared with the U treatment. The U and US treatments under CF irrigation promoted the N uptake of the aboveground rice more than those under mild AWD irrigation.

With different irrigation methods, the effects of urea and rice straw addition on the N absorption of the aboveground rice were varied. Compared with the CK and S treatments, the U and US treatments under CF irrigation significantly promoted the absorption of soil N by rice, while only the S and U treatments had significant differences under mild AWD irrigation. Compared with mild AWD irrigation, the U and US treatments under CF irrigation significantly promoted the absorption of soil N by rice. Regardless of the irrigation and fertilization method, the soil was the main source of N in the aboveground parts of rice, followed by urea and finally rice straw (Fig. 4).

3.4 Cumulative N_2O emissions, rice agronomic properties and yield-scaled N_2O emissions

In addition to the CK treatment, compared with CF irrigation, mild AWD irrigation significantly promoted the accumulation of N_2O during the rice growth period, with an average increase of 28.8% (Table 1). Under CF irrigation, there was no significant difference in the accumulation of N_2O between S and CK or between US and U. However, the addition of rice straw under mild AWD irrigation significantly increased the accumulation of N_2O by 18.1% (Table 1). Compared with the CK and S treatments, the U and US treatments significantly promoted cumulative N_2O emissions under the two irrigation modes. As shown in Table 2, irrigation methods, N application level, and rice straw return affected cumulative N_2O emissions, of which the N application level had the greatest impact. The interaction between irrigation level and N fertilizer or rice straw significantly affected cumulative N_2O emissions.

As shown in Table 1, compared with CF irrigation, mild AWD irrigation significantly reduced rice aboveground biomass under US treatment but had no effect on other treatments. Regardless of whether CF irrigation or mild AWD irrigation was applied, there was no significant difference in the rice aboveground biomass between S and CK or between US and U. Compared with the CK and S treatments, the U and US treatments significantly promoted the rice aboveground biomass under the two irrigation modes. Irrigation level had no effect on rice yield under all treatments. Regardless of CF irrigation or mild AWD irrigation, rice yield under the U and US treatments was significantly higher than that under the CK and S treatments, but there was no difference between the former two and the latter two.

In addition to the CK treatment, compared with CF irrigation, mild AWD irrigation significantly promoted yield-scaled N_2O emissions during the rice growth period. Under urea application conditions, compared with CF irrigation, mild AWD irrigation increased yield-scale N_2O emissions by 17.9%, and the addition of rice straw further promoted yield-scale N_2O emissions by 17.4% under mild AWD irrigation conditions (Table 1). Regardless of CF irrigation or mild AWD irrigation, yield-scaled N_2O emissions under the U and US treatments were significantly higher than those under the CK and S treatments. Rice straw addition had no effect on the yield-scaled N_2O emissions under CF irrigation but significantly increased the yield-scaled N_2O emissions under mild AWD irrigation.

4 Discussion

4.1 Effects of irrigation methods, N levels, and rice straw return on N_2O emissions

N_2O emissions are significantly affected by water-filled pores and mineral N (NH_4^+-N and NO_3^--N) content (Allen et al., 2010). The N_2O emission peak in CF irrigation occurred only after N application, while mild AWD irrigation caused other N_2O emission peaks, which might have been caused by the change in soil moisture conditions by mild AWD irrigation (Zhou et al., 2020). The peak of N_2O after fertilization may be because a large amount of N application increases the soil inorganic N concentration (Fig. 2A and 2C), which in turn promotes the generation of N_2O, which comes from the denitrification process (Wang et al., 2017b; Yano et al., 2014). During the denitrification process, it is easier for microorganisms to use NO_3^--N as an electron acceptor (Fig. 2C), which affects the reduction process of N_2O, resulting in an increase in the ratio of N_2O/N_2 in the denitrification products (Pérez et al., 2000). Our results showed a negative N_2O emission flux at the later stage of rice growth, which may be due to the decrease in surface soil N_2O concentration due to the strengthening of the N_2O reduction process or the weakening of the N_2O diffusion process in the soil profile, which allowed atmospheric N_2O to diffuse back into the soil (Chapuis-Lydie et al., 2007). Mild AWD irrigation promoted cumulative N_2O emissions by 28.8% on average, which was as proposed in our Hypothesis 1. Similar results were found in previous studies, which may be due to the increased N_2O produced by nitrification and denitrification due to water level alternation (Liang et al., 2017; Zhou et al., 2020) and temperature change (Wu et al., 2019) of mild AWD irrigation. To reduce N_2O emissions from paddy fields, researchers generally regulate N_2O production by optimizing N management (Liang et al., 2017), applying inhibitors to control the N supply rate of N fertilizers (Wu et al., 2019). In both CF and mild AWD irrigation, there was no obvious N_2O emission peak at the later growth stage of rice, which may have been due to the decrease in soil inorganic N content (Fig. 2A and 2C) and microbial biomass (Fig. 3A).

Compared with CK and S, N fertilizer application (U and US) significantly increased N_2O cumulative emissions and was the most notable factor in N_2O generation (Table 2), mainly because N fertilizer application provided sufficient substrates for soil nitrification and denitrification to generate N_2O (Fiedler et al., 2017; Wu et al., 2021). The peak of N_2O emissions after base fertilizer application was larger than that after two topdressing, which might have been due to a higher N application rate and simultaneous nitrification and denitrification in initial flooding (Mathieu et al., 2006; Wang et al., 2017b). The peak of N_2O emissions after the two topdressing treatments with CF irrigation was similar, while the peak of N_2O emissions after the first topdressing treatment with mild AWD irrigation was significantly larger than that following the second topdressing treatment. This may be because the soil environment (temperature, moisture, etc.) changed little in long-term flooding under CF irrigation (Lagomarsino et al., 2016; Verhoeven et al., 2018; Congreves et al., 2019), while the variations in the soil environment of the two top dressings under mild AWD irrigation changed the utilization of fertilizer N by microorganisms (Fig. 3B). Therefore, reducing the amount of the first top dressing under mild AWD irrigation and maintaining flooding for approximately one week after fertilization may benefit N_2O reduction (Liao et al., 2020). The negative value of N_2O emissions appeared at the later stage of rice growth, indicating that the paddy field could also become a sink for N_2O (van Groenigen et al., 2015), which might be caused by the lack of N supply at the later stage.

Increasing the second topdressing might be beneficial for alleviating N deficiency (Liao et al., 2020).

Unlike the CF irrigation, the addition of rice straw under mild AWD irrigation conditions promoted N_2O emissions (Table 1), probably because the alternation of wet and dry conditions promoted the decomposition of rice straw (Andren et al., 1993; Buchen et al., 2016; Chen et al., 2016), which was beneficial to the growth of microorganisms (Fig. 3A), thus promoting the production of N_2O (Said-Pullicino et al., 2014; Wang et al., 2018; Wu et al., 2021). In addition, compared with U and S, US promoted microbial absorption of urea and rice straw N (Fig. 3B), which also proved that US treatment was more conducive to the growth of microorganisms.

4.2 Effects of irrigation methods, N levels, and rice straw return on rice production and yield-scaled N_2O emissions

The change in irrigation method did not cause differences in rice yield (Table 1), but under the US treatment, mild AWD irrigation significantly reduced the aboveground biomass of rice and the uptake of soil N by rice (Table 1 and Fig. 4), which was consistent with our Hypothesis 2. Previous studies have also shown that mild AWD irrigation can stabilize or increase rice yield. This may be because mild AWD irrigation can promote the transport of nutrients from stems and leaves to grains during the reproductive growth stage of rice while inhibiting ineffective tillering and increasing the number of effective panicles, thereby reducing excessive vegetative growth of rice (Carrijo et al., 2017; Li et al., 2018b; Liao et al., 2020; Zhang et al., 2009). This may also be an important reason for the decrease in the uptake of soil N by rice under AWD irrigation. Urea application was a key factor in improving rice yield (Wang et al., 2017a) but also aggravated soil N uptake by rice, and soil was the largest source of N for rice in all treatments (Fig. 4). Compared with U, under CF irrigation and mild AWD irrigation, US reduced the uptake of soil-derived N by rice, and the trend was more obvious under mild AWD irrigation. Although the trend was not significant, rice straw return may be an effective way to maintain long-term soil fertility (Fig. 4).

In our study, mild AWD irrigation, urea application and rice straw return all increased yield-scaled N_2O emissions (Table 1), mainly due to improved soil aeration and increased inorganic N and rice straw decomposition, resulting in more N_2O production (Andren et al., 1993; Buchen et al., 2016; Chen et al., 2016; Lagomarsino et al., 2016; Fiedler et al., 2017; Verhoeven et al., 2018; Congreves et al., 2019; Wu et al., 2021). Although mild AWD irrigation had higher yield-scaled N_2O emissions than CF irrigation, the GWP (CH_4 + N_2O) under mild AWD irrigation was significantly lower than that under CF irrigation and decreased by 8.1%, 57.9%, 11.8% and 62.9% under CK, S, U and US, respectively (Table S1). Therefore, mild AWD irrigation combined with rice straw return may be a promising agronomic measure that maintains rice yield, slows greenhouse effects (CO_2 emissions are not considered), and also reduces soil fertility consumption.

5 Conclusions

The effects of irrigation methods, N levels and rice straw return on N_2O emissions were explored through pot experiments using rice. We found that N_2O emissions were affected by urea application and irrigation methods, with urea application being the most important. Compared with CF irrigation, mild AWD irrigation increased cumulative N_2O emissions, with an average increase of 28.8%. In addition, adding rice straw to mild AWD irrigation further stimulated N_2O emissions by 18.1%. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation increased the yield-scaled N_2O emissions by 17.9%, and the addition of rice straw further promoted the yield-scaled N_2O emissions under mild AWD irrigation by 17.4% but reduced the GWP (CH_4 + N_2O) by 62.9%. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation reduced the uptake of soil-derived N and aboveground biomass of rice but did not reduce rice yield. Therefore, mild AWD irrigation combined with rice straw return may offer a promising agronomic measure to maintain high rice yield, reduce greenhouse effects, and maintain or improve soil fertility.

Data availability. Original data are available upon request. Material necessary for this study's findings is presented in the paper.

Author contributions. Kaikuo Wu, Wentao Li, Zhanbo Wei and Zhi Dong conceived and designed the experiments; Yue Meng and Na Lv performed the experiments; Kaikuo Wu analyzed the data; Kaikuo Wu and Lili Zhang wrote the paper and all authors approved submission of the paper. All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Review statement.

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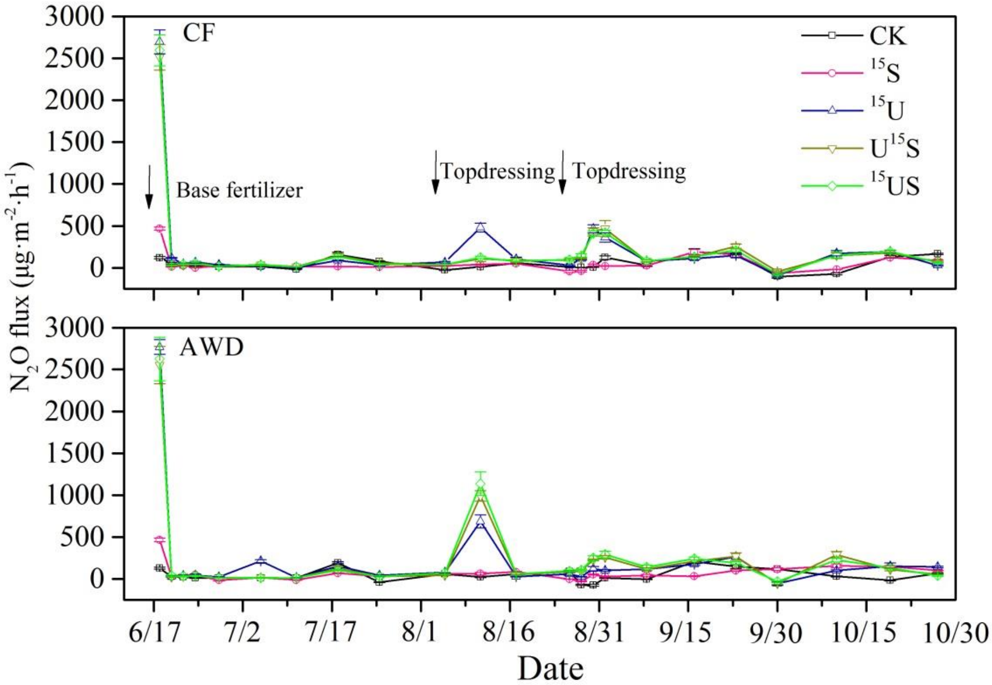
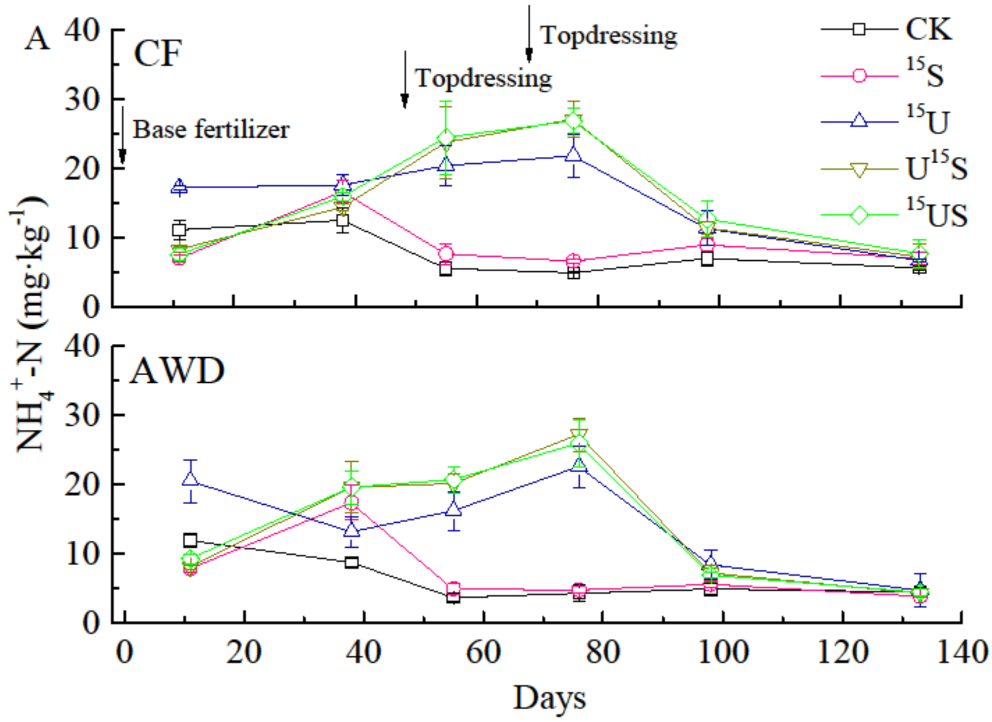


Fig. 1 Effects of different treatments on nitrous oxide (N_2O) flux. Bars represent standard errors (n=3), the same below.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CF
AWD
Base fertilizer
Topdressing
Topdressing
CK
15S
15U
U15S
15US
NH4+-N (mg·kg-1)
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100
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140
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10
20
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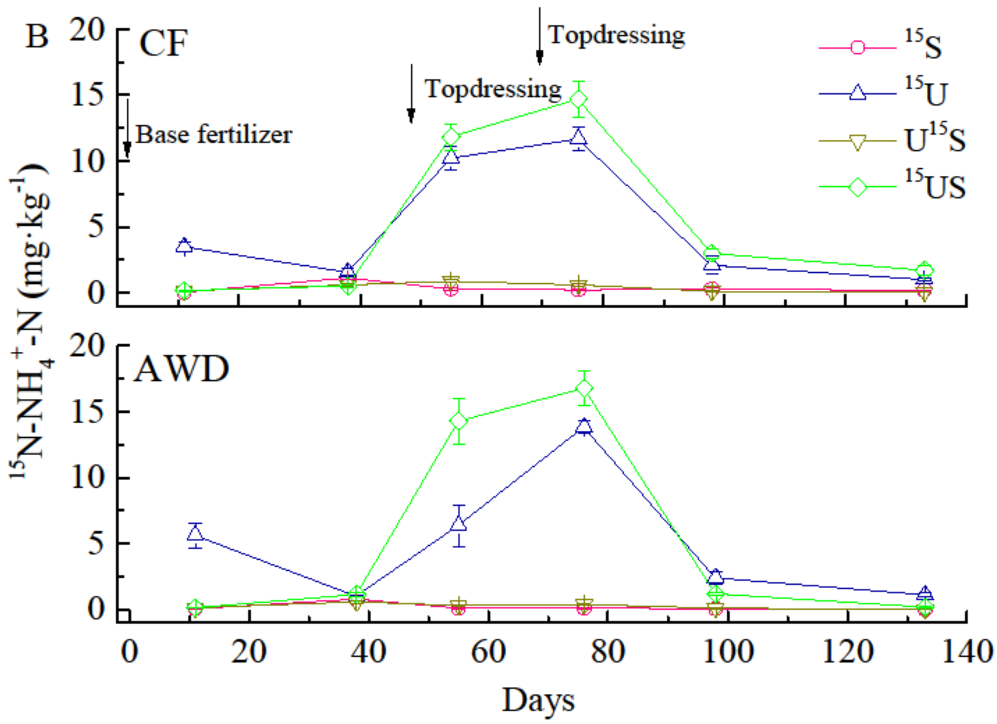
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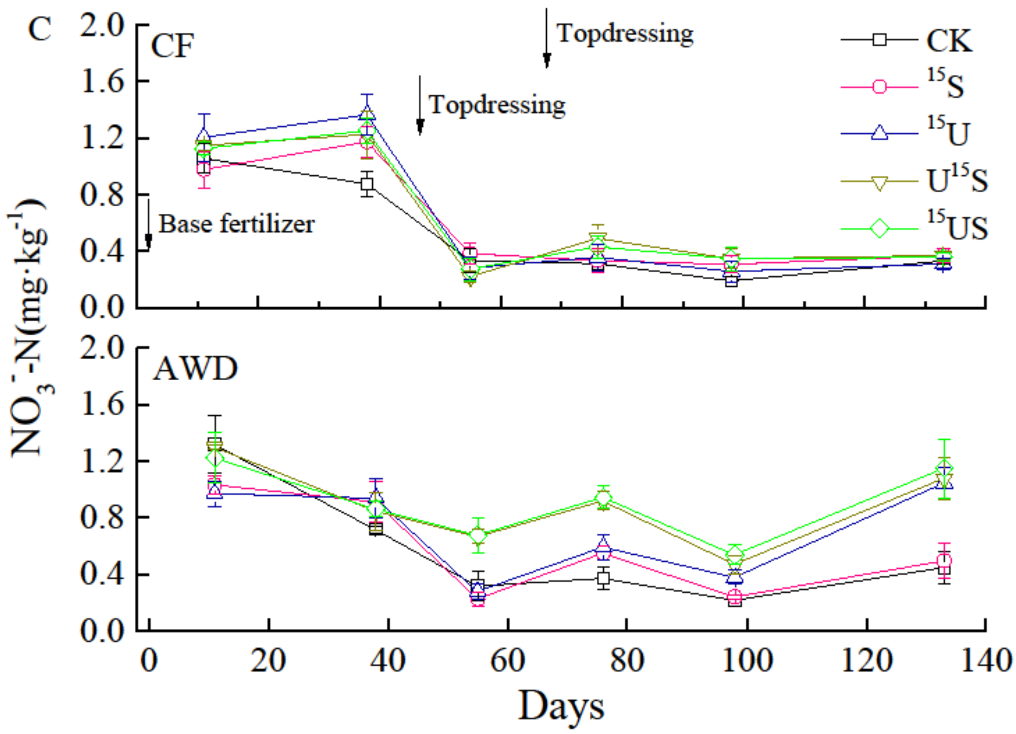
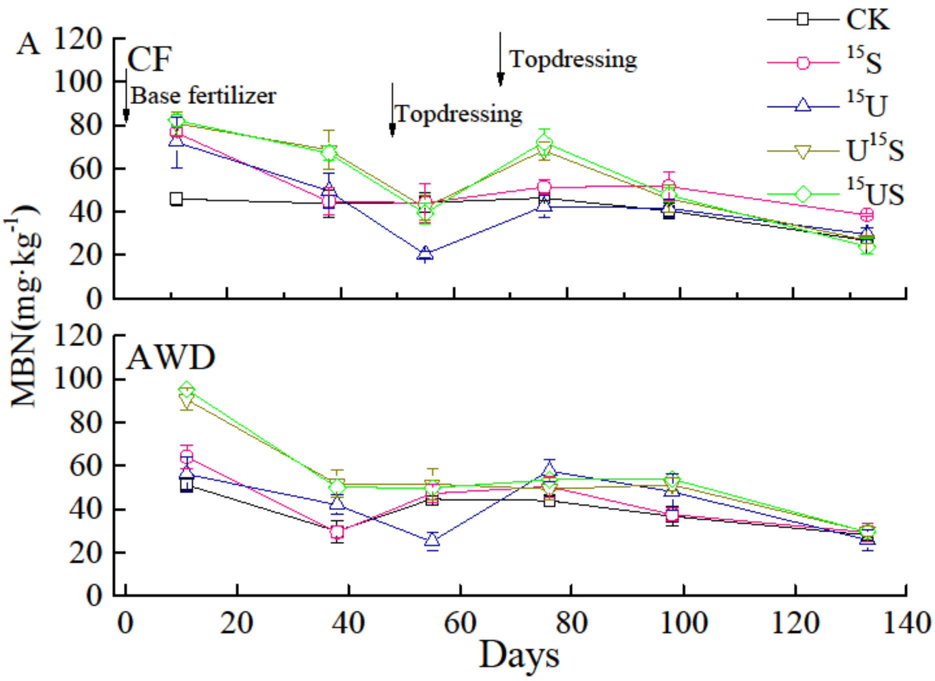


Fig. 2 Changes in soil ammonium nitrogen (NH_4^+-N) concentration (A), the contribution of ^{15}N markers to NH_4^+-N (B) and changes in soil nitrate nitrogen (NO_3^--N) concentration (C) during the growth period of rice (n=3).



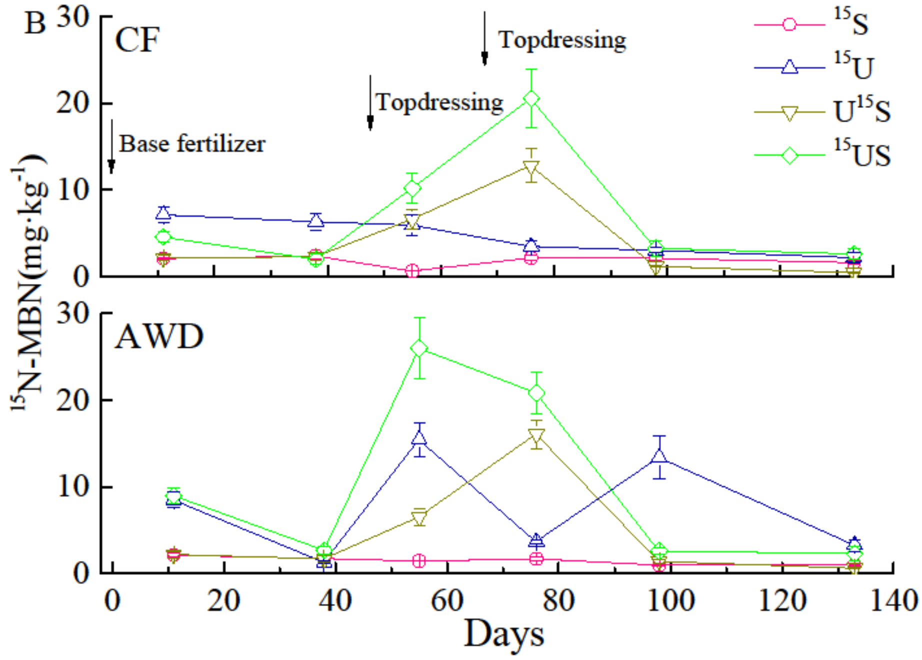


Fig. 3 Changes in the concentration of microbial biomass N (MBN) (A) in the soil during the rice growth period and the contribution of ^{15}N markers to MBN (B) (n=3).

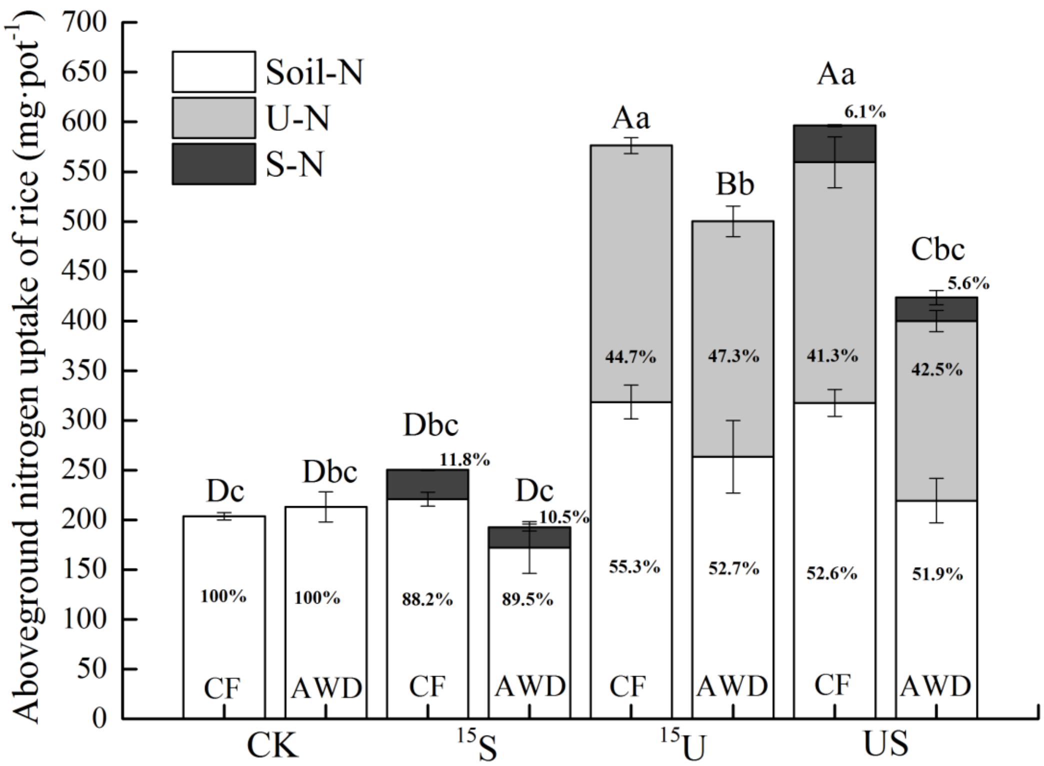


Fig. 4 The source of nitrogen in the aboveground biomass of rice at the maturity stage (n=3). CF: continuous flooding irrigation, AWD: mild alternate wetting and drying irrigation, Soil-N: Soil derived nitrogen, U-N: Urea derived nitrogen, S-N: Rice straw derived nitrogen. Different capital letters indicate significant differences in total nitrogen uptake of rice above ground (P < 0.05), and different lower case letters indicate significant differences in soil nitrogen supply (P < 0.05).

Table 1 Effects of different treatments on cumulative nitrous oxide (N_2O) emissions, rice aboveground biomass, rice yield and yield-scaled N_2O emission. The values denote means ± standard errors (n=3). Different lowercase letters indicate significant differences ($P < 0.05$).

Treaments		Cumulative N_2O emissions kg ha^{-1}	Rice aboveground biomass g pot^{-1}	Rice yield g pot^{-1}	Yield-scaled N_2O emission g kg^{-1}
CF	CK	1.48±0.06 ef	37.11±2.53 f	21.63±1.81 b	0.24±0.01 d
	^{15}S	1.24±0.05 f	37.99±2.69 f	20.91±1.63 b	0.21±0.03 d
	^{15}U	4.02±0.30 c	82.54±10.39 ab	36.56±2.75 a	0.39±0.04 c
	U+^{15}S	3.89±0.09 c	87.58±7.70 a	35.98±1.72 a	0.38±0.02 c
	^{15}U+S	3.76±0.02 c	80.99±19.54 abc	35.85±2.50 a	0.37±0.03 c
AWD	CK	1.64±0.15 e	45.31±3.07 ef	22.92±1.07 b	0.25±0.02 d
	^{15}S	2.07±0.17 d	34.78±4.86 f	20.42±0.46 b	0.36±0.02 c
	^{15}U	4.48±0.12 b	64.44±7.33 bcd	34.81±1.64 a	0.46±0.03 b
	U+^{15}S	5.05±0.28 a	62.92±2.49 cde	34.50±1.76 a	0.53±0.01 a
	^{15}U+S	5.29±0.25 a	60.44±6.74 de	34.85±1.18 a	0.54±0.03 a

Table 2 Cumulative nitrous oxide (N_2O) emissions in response to irrigation method, nitrogen level, and straw returning. * indicated significant treatment effects within a main category ($P < 0.05$), *** indicated significant treatment effects within a main category ($P < 0.001$).

Factors	Cumulative N_2O emissions
Irrigation method (I)	88.576***
Nitrogen level (N)	1525***
Straw (S)	6.393*
I×N	6.275*
I×S	26.288***
N×S	1.426
I×N×S	0.178